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(54) Title: A COMPLEX SUPERCONDUCTING QUANTUM INTERFERENCE DEVICE AND CIRCUIT

(57) Abstract

The disclosed complex SQUID circuit achieves a high signal gain and high sensitivity for detecting a weak magnetic field. It is characterized by concentric loops (60, 62, 64, 66, 68, 70) of superconducting material, each loop incorporating preferably a pair of Josephson Junctions (76), the Josephson Junctions (76) all aligned in a diameter generally transverse to the diameter defined by the connectors (78, 80) interconnecting the loops (60, 62, 64, 66, 68, 70).

A COMPLEX SUPERCONDUCTING QUANTUM INTERFERENCE DEVICE
AND CIRCUIT

TECHNICAL FIELD

This invention relates in general to superconducting
quantum interference devices, known as SQUIDs, used for
measurement of a magnetic flux. In particular, it relates a
new, complex type of superconducting quantum interference
device and circuit.

BACKGROUND ART

Superconducting QUantum Interference Devices (SQUIDs) are
the most sensitive magnetic field detector known. They
involve several quantum phenomena, namely, Josephson
tunneling, flux quantization, and quantum interference. A
SQUID can be configured to measure a minute change of any
physical quantity that can be converted to a flux, such as
voltage, current or magnetic field; i.e. it is extremely
versatile, being able to measure the magnetic field produced
by any of various field sources. Such devices can have energy
resolution capabilities approaching the quantum limit. As a
result, the SQUID has been used in a wide variety of
applications, ranging from medical diagnosis to scientific
research, and from non-destructive evaluation to routine
measurements of magnetic properties of materials.

There are two kinds of SQUIDs. The first, the dc SQUID,
usually consists of two Josephson Junctions connected in
parallel on a superconducting loop. The second, the rf SQUID,

usually involves a single Josephson Junction on a superconducting loop. In both types, the Josephson Junction is formed by a thin insulating barrier or layer between two pieces or sections of the superconductive loop. The

5   insulating barrier's thickness and cross-section are so very much smaller than the dimensions of the complete circuit loop that electron pairs can tunnel from one side of the Junction to the other without transfer of energy; i.e. when the thickness of the Josephson Junction reaches the order of the

10   coherence length of electron pairs, a superconducting tunnelling current occurs, which is a striking evidence for the existence of long-range order in the superconducting state. This makes it possible to have current flow in the absence of an applied voltage. Particularly in the dc two

15   Junction loop SQUID, the current produced by interference oscillates with changes in the magnetic field.

Typically, a SQUID produces an output voltage which varies in a periodic manner in response to a small input flux. The extreme sensitivity of such a device derives from the fact

20   that the SQUID can resolve a small fraction of ϕ_0, the quantum of magnetic flux, while ϕ_0 is itself a very small quantity. Both dc and rf SQUIDs are used, and can be used, as sensors in a wide variety of instruments.

A multi-channel array of SQUIDs was first proposed by

25   Feynman in The Feynman Lecturers on Physics-Quantum Mechanics, Addison Wesley Publishing Co., 1965, Ch. 21, and pursued by various research groups; see J.E. Zimmerman and A.H. Silv r, Macroscopic Quantum Interference Effects Through

Superconducting Point Contacts, Physical Review, Vol. 141, No. 1, Jan. 1966, and W.H. Chang, Interferometric Measurement of Magnetic Flux, IBM Technical Disclosure Bulletin, Vol. 25, No. 6, Nov. 1982, pp. 2940-2941.

5   In general, a SQUID can be used to sense a magnetic field directly. However, in many circumstances when this is not a practical arrangement, the SQUID is magnetically coupled to the field by means of a flux transformer. The flux transformer is a closed superconducting circuit which has a

10   primary for sensing the field and a secondary which is magnetically coupled to the SQUID. The principle reason is simply the need to minimize detection of ambient noise. A detection coil responds to the applied field regardless of the distance of its source. With the detection coil of first

15   order or higher, it makes much less demands with regard to screening. The signal thus generated in the SQUID is then fed via electrical leads of normal conducting material to be connected to electronic circuitry for further processing. For some applications, it is of advantage to integrate the

20   external circuit along with the SQUID on a single substrate. There are also situations in which it is possible to configure the SQUID itself to perform some particular function, such as in a magnetometer, gradiometer, susceptometer, or voltmeter. More detailed principles can be found in earlier reviews by

25   Clarke, SQUIDs: Principles, Noise, and Applications, in Superconducting Devices, edited by Steven T. Ruggiero and David A. Rudman, Academic Press, Inc., 1990, pp. 51-99, and Clarke, SQUIDs: Theory and Practice in the New

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Superconducting Electronics, edited by H. Weinstock and R.W. Ralston, Kluwer Academic Publishers, 1993.

Up to late 1986, it was believed that superconductivity above a temperature of 40 degrees kelvin (k) was not possible,

5   according to the BCS theory. A breakthrough in critical temperature in superconductivity was made in Nov. 1986, by Bednorz and Muller; see J.G. Bendnorz and K. Alex Muller, Z. Phys., B 64, 189, 1986. Now the transition temperatures of new superconductors reach well above one hundred degrees

10   kelvin; see Hasen et al., Phys. Rev. Lett. 60, 1657, 1988, and Parkin et al. Phys. Rev. 60, 2539, 1988. Since the discovery of High-Tc Superconductors, the basic mechanism for high-Tc superconductivity has been far from understood, which may well be somewhat different from the mechanism of low-Tc

15   superconductivity, if not completely different. Although today we have very limited understanding of high-Tc materials, it has generally been accepted that SQUIDs are the most promising application for these materials. With the critical temperature of High-Tc Superconductor (HTSC) now above the

20   boiling point of liquid nitrogen, the HTSC SQUID can operate in liquid nitrogen, which is much less expensive cryogen with a much higher heat capacity as compared to liquid helium. This drastically reduces the operating cost for the device. Such a High-Tc SQUID certainly is more versatile, feasible and

25   economically practical in application.

Unfortunately, realization of this application has been hampered due to a number of unsolved technical challenges.

The first problem is lack of a reliable technique for fabricating the Josephson Junction; this is the essential element of a vast majority of traditional superconducting electronics. A classic Josephson Junction is extremely difficult to fabricate with HTSC. The main reason for this problem is the very small coherence length of the oxide superconductors which is typically on the order of 1nm. Hence, to fabricate a good Junction it is necessary to have a S-I interface on an atomic scale. The alternative weak link Junction structure, relying on such linear dimensions, is very hard to fabricate even with the most sophisticated lithographic tools available today. Though dc-SQUIDs fabricated with grain boundaries have shown some substantial progress, it is not clear that such a technique can be extended to producing complex circuits.

The second problem concerns the 1/f noise level in HTSC SQUIDs; it is very high compared with that of low temperature SQUIDs. This noise clearly originates in the Josephson elements, and not in the epitaxial HTSC films, for reasons that are not understood.

The third problem is that the characteristic voltage is low, which might be due to the weak tunnelling current. This further lowers the signal-to-noise ratio.

It is difficult to imagine that HTSC SQUIDs will have significant practical applications unless there is a major improvement in their signal-to-noise ratio and sensitivity. In order to achieve a high-performance SQUID with high-Tc superconductors, it is important to enhance the magnitud of

the signal gain and the S/N ratio. Equally important is to improve the pattern of oscillation, i.e. the slope of the curve.

5   Accordingly, an object of the present invention is to provide a SQUID design, particularly a HTSC SQUID design, which will achieve a high current gain, high signal-to-noise ratio and high sensitivity.

These and other objects of the invention will be apparent to those of ordinary skill in this field from the following
10   description of preferred embodiments.

SUMMARY OF THE INVENTION

The new SQUID design is based on two different schemes. The first one changes the structure of the Josephson Junction in the loop. The second provides for a particularly
15   advantageous configuration of the SQUID circuit. These two schemes can be used either separately or in combination. The fabrication of these SQUIDs should prove to be both reproducible and reliable.

Preferably, the SQUID device of the present invention is
20   formed on the face of a substrate. It includes a loop of superconducting material of a first width, and a Josephson Junction formed in the loop by pads of superconducting material overlying one another and separated by a layer of insulating material, the pads each having a second width
25   substantially identical to one another and larger than the first width. The layer of insulating material may be

substantially larger than the pads; in fact, the layer of
insulating material may extend from one pair of pads across
the loop to the other pair of pads, if desired.

Preferably the SQUID device of the present invention is

5   configured as a plurality of concentric loops on the face of
the substrate, the loops being equally spaced from one another
and connected in parallel by radial conductors extending on a
common diameter away from the center of the loops, this
diameter being preferably perpendicular to a second diameter

10   along which is positioned the Josephson Junctions in the
succession of loops. Such an arrangement offers a high
current gain, high signal to noise ratio and high sensitivity.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be further described in connection

15   with the accompanying drawings in which:

FIG. 1 is a schematic illustration of a typical DC SQUID
of the prior art;

FIG. 2 is a schematic illustration of a typical DC SQUID
magnetometer of the prior art;

20   FIG. 3 is a schematic illustration of a typical voltmeter
SQUID of the prior art;

FIG. 4 is a schematic illustration of a typical
gradiometer SQUID of the prior art;

FIG. 5 is a schematic illustration of an output voltage

25   characteristic of a SQUID;

FIG. 6 is a schematic illustration of an improved SQUID
constructed in accordance with the present invention;

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FIG. 7 is a cross-sectional view taken on lines VII-VII of FIG. 6;

FIG. 8 is a schematic illustration of another construction of the improved SQUID of the present invention.

5   FIG. 9 is a cross-sectional view taken on lines IX-IX of FIG. 8;

FIG. 10 is a schematic illustration of an improved SQUID circuit of the present invention;

FIG. 11 is a schematic illustration of the SQUID circuit

10   shown in FIG. 10 on a substrate;

FIG. 12 is a cross-sectional view taken on lines XII-XII of FIG. 11 showing one construction of a SQUID element which may be employed in this circuit; and

FIG. 13 is a cross-sectional view, similar to FIG. 12,

15   showing another construction of a SQUID element.

DETAILED DESCRIPTION

The present invention provides a SQUID device and design, particularly a HTSC SQUID design, that achieves high current gain, high signal-to-noise ratio and high sensitivity. Its

20   significance can best be appreciated by comparing it first to a typical dc SQUID, such as the dc SQUID construction shown in FIG. 1. As there are illustrated, a loop 2 of superconducting material on the face of substrate 3 is broken at Josephson Junctions 4 typically on opposed sides of the loop, each

25   Josephson Junction being formed by a thin insulating barrier or layer. Such a construction shown is, f r example, in Takagi et al. U.S. Patent No. 5,077,266 issued Dec. 31, 1991

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and titled "Method of Forming Weak-Link Josephson Junction."
Connectors 6 extend from opposed sides of the loop to permit
the current flowing through the loop to be detected in a well-
known fashion. A typical material used to fabricate the

5   connectors 6 is yitrium barium copper oxide ($YBa_2Cu_3O_7$).
Typically the Josephson Junction is of a dimension (width and
height) comparable to these dimensions of the superconductor,
but its length (or thickness) is small. This complicates
fabrication of the Junction and appears to contribute

10   significantly to the problems associated with HTSC SQUIDs.

        SQUID elements have been used in a variety of devices.
For example, as indicated in FIG. 2 it is known to place a
SQUID element within a low temperature environment and to
translate to that environment an external magnetic field using

15   an external pick-up loop 12 connected by conductors 14 to an
internal input coil 16 adjacent to the SQUID. Thus, a
magnetic field encountered by pick-loop 12 will be translated
to a generated magnetic field by input coil 16 which in turn
will effect the SQUID, thereby constituting the sensor of a

20   magnetometer.

        As shown in FIG. 3, a SQUID device also may be employed
in a voltmeter. In general, such a construction provides a
pair of terminals 22 to which the voltage may be applied,
these terminals being connected across a resistor and

25   capacitor in parallel with one another to an input coil 24
which is adjacent the SQUID thereby applying the magnetic
field it generates to the SQUID. This magnetic fi ld will be

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proportional to the voltage applied across terminals 22 which in turn will cause a corresponding signal in the SQUID.

A SQUID device also is can be employed in a gradiometer as shown in FIG. 4, the device in this arrangement sensing the 5 difference or gradient in a magnetic field between a first pick-up loop 26 and a second pick-up loop 28 which are both connected as indicated to an input coil 30. Thus, the difference in magnetic fields encountered by the two pick-up loops will produce a different magnetic field that is sensed 10 by the SQUID causing it to produce a corresponding signal.

SQUID elements are known to produce a characteristic voltage versus flux signal in response to an implied field at a constant bias current. This voltage varies in an oscillation pattern, as shown in FIG. 5 with a period of 15 magnetic flux.

Shown in FIGs. 6 and 7 is a preferred form of SQUID constructed in accordance with the present invention. It consists of a loop 42 of superconducting material on a substrate 43, the loop being broken, preferably on opposed 20 sides, and enlarged to form pads 44. Between overlapping pads 44 is provided the insulating material 45. Thus, by this construction the characteristics of the Josephson Junction are not limited in size to the size of the superconducting loop, but rather may be adjusted as desired to achieve a Junction of 25 the preferred characteristics irrespective of the size of the superconducting loop. Connectors 46 extend from either side of the loop. Thus, on application of a flux B in any direction, such as that indicated by arrows 48, and

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particularly upon changes in that flux, changes in the superconducting current flowing in loop 42 will occur and may be sensed on correctors 46.

To fabricate the form of SQUID shown in FIG. 6, as shown in FIG. 7 a superconducting thin film 42' is deposited on the face of a substrate, and is patterned to obtain a half SQUID circuit with two enlarged terminal pads 44. Then an insulating layer 45 is formed on the enlarged terminal pads with the thickness controlled to be in the range compatible to the coherence length scale; this can be achieved by conventional techniques without difficulty.

Then a superconducting thin film 42" is deposited to cover this barrier layer and is patterned to obtain the other half of the SQUID circuit with enlarged terminal pads exactly on the top of terminal pads of film 42'. The Josephson Junction is formed by the two enlarged terminal pads 44 of substantially the same size and coupled by an insulating layer 45. This geometry is totally different from that of standard end-to-end Josephson Junctions. The tunnelling current in this SQUID is virtually perpendicular to the supercurrent in the loop, which is entirely different from that in a conventional SQUID. This planar type Josephson Junction offers significant advantages in the process of fabrication, for it is relatively easy to apply and control. Also, the cross-sectional area of the active barrier Junction is obviously many orders of magnitude greater than that of prior art constructi ns. This leads to additi nal advantages for a

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SQUID which enable the SQUID construction of this invention to enhance the junction current enormously.

Shown in FIG. 8 is another construction of SQUID employing the principals of the present invention. In this construction, the superconducting loop 52 on substrate 53 is enlarged to provide pads 54 between which is the insulating material 56. In this construction, however, the material does not just cover the pad areas, but rather extends across the face of the planar element. The remaining portion 52" of the superconducting circuit is applied on top of this pad to achieve the other half of the superconducting loop. Connectors 58 extend from opposed sides of the loop.

To fabricate this construction, as shown in FIG. 9 preferably after the first half 52' of the superconducting loop is applied to the substrate. Then, instead of an insulating layer being formed only on the top of the enlarged terminal pads, an insulating layer 56 covering the two bottom enlarged terminal pads 54' is formed to extend over half of the substrate; its thickness is in the range of coherence length. Then a superconducting layer 52" is deposited on the insulating layer 56, and is pattern to obtain the other half loop of the SQUID with enlarged terminal pads 54" exactly on overlying pads 54'.

Basically, this provides two half SQUID loops on two separate superconducting film layers coupled by an insulating layer. The size of the insulating layer is not critical as long as it covers the enlarged terminal pads. This construction avoids the need to accurat ly apply or define the

insulating layer, further simplifying fabrication of the SQUID
of the present invention.

These SQUID constructions can be advantageously employed
in various circuit configurations such as those circuits shown
5   in FIGs. 2, 3 and 4 for a magnetometer, a voltmeter or a
gradiometer.

The SQUID loops previously described may be cascaded or
multiplied in any of various ways. In general, such cascading
is intended to increase the combined output of the cascaded
10   loops in response to a very weak magnetic field, for as
previously stated SQUID circuit and loops are often used to
sense exceedingly weak magnetic fields. In general, an
exceedingly weak magnetic field may be thought of as a very
weak magnetic flux line surrounded by a few still weaker
15   echoes of that line. As this flux line interacts with a SQUID
loop or circuit, it will result in a current flow across the
Josephson Junctions of the circuit. The current flow will be
the greatest for the junctions nearest to the magnetic flux
line, and significantly less for Josephson Junctions spaced
20   from that flux line. Many previous circuit arrays of SQUID
loops place the loops in an adjacent or side-by-side
relationship. Thus, as the magnetic flux line moves relative
to this array, it will produce a maximum current flow in
various successive junctions of the array. Many Josephson
25   Junction or SQUID circuits combine this current flow such that
as the interaction of the flux line sweeps across the array
the decrease in current flow of a pr vious loop will be offset
by an increase in current flow in the current loop, thus

resulting in a substantially uniform signal as the flux line traverses at least the center portion of the array.

It is often desirable to not smear the signal generation effect of the flux line as it moves across the array, but

5   rather to construct or interconnect the SQUID circuits of the array in a fashion designed to maximize the output of the circuit on resulting from the flux line when it is substantially centered on the array, and to minimize the result in the smearing of this signal as the flux line moves

10   beyond this mid-point. In other words, it is often desirable to provide a current flow output from the SQUID circuit that closely tracks the location of the flux line relative to the array and also indicates with sensitivity the strength of that flux line.

15   A preferred circuit for achieving this result is shown in FIG. 10, and as applied to the face of a substrate in FIG. 11. In general, it consists of a plurality or multiplicity of nested SQUID circuits which for convenience have been labelled 60, 62, 64, 66, 68 and 70. These SQUID circuits are nested

20   (or are concentric) with one another, all being centered on an imaginary point 74. Each SQUID circuit includes a pair of Josephson Junctions 76 along a line or diameter across the concentric SQUID circuits. The concentric SQUID circuits are interconnected by a set of connectors 78 and 80, these

25   connectors preferably being superconductive and also lying on a common line across the concentric SQUID circuits, this line or diameter being substantially perpendicular to the line

d fined by Josephson Junctions 76. Thus, as a line of

magnetic flux moves across the circuit, in an ideal situation

it might pass along a diameter, crossing center point 74 then

moving out of the concentric SQUID circuits along the same

5   diameter. The current output (or signal) produced by the

Josephson Junctions in general will be directly related to the

strength of the magnetic flux line and its proximity to the

Josephson Junctions. A maximum output will be achieved when

the magnetic flux line is at the center point 74 of the

10   circuits. This output will rise as the flux line moves

towards that center, and decrease as it moves away from that

center. In contrast, many of the SQUID circuits proposed or

employed by others in this field significantly fail to produce

a distinct output peak when the flux line is centered on the

15   array, but instead smear the output as the flux line moves

across the array.

        Preferably this SQUID circuit is applied to the face 84

of substrate 86, as shown in FIG. 11. The connectors 78 and

80 each terminate in a contact pad 88.

20   As shown in FIG. 12, the Josephson Junction elements of

this SQUID circuit may be formed by interrupting a

superconductor 90 to provide an insulating layer 92. This

insulating layer 92 may be of a width substantially equal to

the width of the superconductor 90, as often done in previous

25   constructions, or it may be enlarged for the reasons

previously described in this detailed description.

        In general, the concentric SQUID circuit preferred by the

present inventi n provides symmetrical concentric loops with a

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common center, thereby enhancing the effect of a magnetic field on the signal output, especially the effect of a non-uniform or discrete magnetic field. The concentric multiplicity of SQUID loop circuits assists significantly in

5   keeping the signals produced on connectors 78 and 80 in coherent phases. This arrangement also increases the effective area of the loops and circuit, while keeping the inductance small for each loop. It therefore provides a considerably greater pattern slope and amplitude for the

10   output voltage over that provided by such arrangements as shown in FIGs. 1-4 and diagrammatically illustrated in FIG. 5.

       FIG. 13 illustrates a different construction of the Josephson Junction, one in which the insulating layer 92' not only engages the end of the superconducting loop 90' but also

15   overlies its end area thereby increasing the effective size of the Josephson Junction in superconductor 90', especially when this construction is coupled with one which maximizes the width of the Josephson Junction. By making it wider than the width of superconductor 90', a maximum signal output can be

20   achieved for a given strength of magnetic fields or magnetic flux line.

       The Josephson Junction employed in this circuit may use any of various constructions or geometry, such as weak link, grain boundary or step edge geometry, as shown in DiLorio et

25   al. U.S. Patent No. 5,134,117, dated July 28, 1992, for a HIGH TEMPERATURE MICROBRIDGE SUPERCONDUCTOR DEVICE UTILIZING STEPPED EDGE-TO-EDGE SNS JUNCTION, Shinada U.S. Patent No. 5,227,645, dated July 13, 1993 for a DC SQUID ELEMENT WITH

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QUASI-PLANAR-TYPE JOSEPHSON JUNCTION, Marsden U.S. Patent No.

5,202,630, dated April 13, 1993, for a THIN FILM SQUID

DETECTOR INCLUDING A LOOP RESPONSIVE TO A MAGNETIC FLUX

COMPONENT LYING IN THE PLANE OF THE THIN FILM, Marsden US

5   Patent No. 5,142,229, dated August 25, 1992, for THIN

FILM...SQUID DETECTORS, Takagi et al. U.S. Patent No.

5,077,266, dated December 31, 1991, for a METHOD OF FORMING

WEAK-LINK JOSEPHSON JUNCTION, AND SUPERCONDUCTING DEVICE

EMPLOYING THE JUNCTION, Kapitulnik U.S. Patent No. 5,219,826,

10   dated June 15, 1993, for a SUPERCONDUCTING JUNCTIONS AND

METHOD OF MAKING SAME, Young et al. U.S. Patent No. 4,418,095,

dated November 29, 1983, for a METHOD OF MAKING PLANARIZED

JOSEPHSON JUNCTION DEVICES, Hed U.S. Patent No. 5,171,732,

dated December 15, 1992, for a METHOD OF MAKING A JOSEPHSON

15   JUNCTION, Ishibashi et al. U.S. Patent No. 4,888,622, dated

December 19, 1989, for a SUPERCONDUCTOR ELECTRON DEVICE, Wang

et al. U.S. Patent No. 4,509,146, dated April 2, 1985, for a

HIGH DENSITY JOSEPHSON JUNCTION MEMORY CIRCUIT, or Tarutani et

al. U.S. Patent No. 4,319,256, dated March 9, 1982, for a

20   JOSEPHSON JUNCTION ELEMENT.

In summary, the preferred SQUID circuit of the present

invention incudes a plurality of concentric superconducting

loops, each superconducting loop consisting of two Josephson

Junctions preferably aligned with one another on a diameter

25   across the loops that is perpendicular to the diameter defined

by the interconnecting conductors of the circuit. The

Josephson Junction elements in this arrangement can be a thin

barrier structure, a point contact structure, a micro-bridge

or a three-layer structure; indeed, the invention is equally

applicable to all sorts of Josephson Junction elements.

Appropriate substrates include sapphire and magnesium oxide.

Multiple concentric non-equally sized loops are provided and

5   are preferably formed on the same superconducting layer. Of

course, they could also be formed on different superconducting

layers, if desired.

        The sensitivity of a SQUID device or circuit is

determined from the equation:

10                              $\phi = B \cdot A$

where ϕ is the flux, B the magnetic field strength and A the

area. Thus, the sensitivity of the SQUID is increased by

increasing the area for a given flux change ($\Delta\phi$); the larger

the area, the smaller the flux change which can be detected.

15   But the largest area that can be used is limited by the

self-inductance (L) of the SQUID. Specifically:

                          $\Delta I_c = \phi_0 \div L$

The larger the area, then the smaller the signal change; the

FIG. 5 fluctuations flatten with increasing area. Thus, SQUID

20   device and circuit design don't use large areas, and have to

otherwise try to deal with low S/N ratios and a reduced

sensitivity.

        The present design effectively enables a large area (A)

to be used in a highly sensitive device and circuit, for it

25   breaks up what would otherwise be the large area into discrete

SQUID elements. Among other things, this arrangement achieves

an excellent match for the input coil 16 or 30 used to

transfer or translate an external field to a SQUID device or

circuit contained within a cryogenic environment or chamber. Because of its reduced, or minimum, size it minimizes the cryogenic chamber's size. Whereas other SQUID designs and circuits as a practical matter are limited to about six loops,

5   because of the area they require, the present design is not so limited. For these reasons, too, the present design enhances the characteristics of the resulting device and circuit.

While this device or circuit is designed for high-Tc superconductors such as YBCO operating in a liquid nitrogen

10   coolant, it also can be employed using low-Tc superconductors. The loops of course can be of any or various shapes other than that illustrated, such as for example, being concentric circles rather than in concentric squares. Each of the concentric loops preferably is separated from adjacent loops

15   by equal spaces, although in certain applications it may be advantageous to vary the space between adjacent loops, or even to vary their centerpoint while maintaining the surrounding relationship of each loop with the inwardly adjacent loop. The conducting lines 78 and 80 can be on the same layer as the

20   loops, and formed by either normal conductors (such as gold), or by a superconductive material. Also, each loop may have a separate conducting line or can be made on different layers. With this loop arrangement, an ultra high sensitivity and accuracy of measurement can be achieved as the result of the

25   greatly enhanced signal gain and improved response characteristics for the device, rendering it especially suitable for neuromagnetism and geophysical magnetism applications.

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CLAIMS

1.   A SQUID device including:

a plurality of loops (60, 62, 64, 66, 68, 70) of
superconducting material being arranged in concentric
alignment with one another,

5   a plurality of Josephson Junctions (76) in each of
said plurality of loops of superconducting material, each
Josephson Junction being formed in a segment of its
respective loop and each Josephson Junction lying
substantially transverse to the direction of its loop

10   segment, said plurality of Josephson Junctions being
aligned with one another such that they all lie in
substantially a straight line extending across the
plurality of concentric loops, and

means (78, 80) electrically connecting the plurality

15   of concentric loops to produce an output proportional to
the current flow in the superconducting material of said
loops.

2.   A SQUID device as set forth in claim 1, in
which each loop (60, 62, 64, 66, 68, 70) includes a pair
of said Josephson Junctions (76).

3.   A SQUID device as set forth in claim 1, in
which said plurality of Josephson Junctions (76) in each
loop (60, 62, 64, 66, 68, 70) are on opposite segments of
the loop.

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4.   A SQUID device as set forth in claim 1, in which the Josephson Junction is formed from an insulating material (92') having a cross-sectional area that is substantially larger than the cross-sectional area of the

5   adjacent portion of the loop of superconducting material (90').

5.   A SQUID device as set forth in claim 1, in which the means electrically connecting said plurality of concentric loops (60, 62, 64, 66, 68, 70) includes connectors (78, 80) extending across said loops in a line

5   substantially perpendicular to the line defined by the Josephson Junctions (76).

6.   A SQUID device as set forth in claim 1, in which there are at least two concentric loops (60, 62, 64, 66, 68, 70) of superconducting material.

7.   A SQUID device as set forth in claim 1, in which said plurality of concentric loops (60, 62, 64, 66, 68, 70) are separated from one another by equal spacing.

8.   A SQUID device as set forth in claim 1, in which said plurality of concentric loops (60, 62, 64, 66, 68, 70) are substantially square in shape and centered on the same point (74).

9.   A SQUID device as set forth in claim 1, in which the means (78, 80) electrically connecting said plurality of concentric loops is also a superconducting material.

10. A SQUID device as set forth in claim 1, in which each of said plurality of Josephson Junctions (76) is formed as pads of superconducting material (90') separated by a pad of insulating material (92').

11. A SQUID device as set forth in claim 10, in which the width of said pad of insulating material (92') forming each Josephson Junction (76) is greater than the width of the pads of superconducting material (90').

12. A SQUID device as set forth in claim 10, in which the widths of the pads of superconducting material (90') forming each Josephson Junction (76) are substantially the same size.

13. A SQUID device as set forth in claim 10, in which the pad of insulating material (92') forming each Josephson Junction (76) is sandwiched between a pair of pads of superconducting material (90').

1/3

Fig. 1
(PRIOR ART)

Fig. 2
(PRIOR ART)

dc SQUID

Fig. 3
(PRIOR ART)

dc SQUID

V(Φ)

Fig. 4
(PRIOR ART)

dc SQUID

Fig.5
(PRIOR ART)

V

0   1   2   3   4

Φ/Φ₀
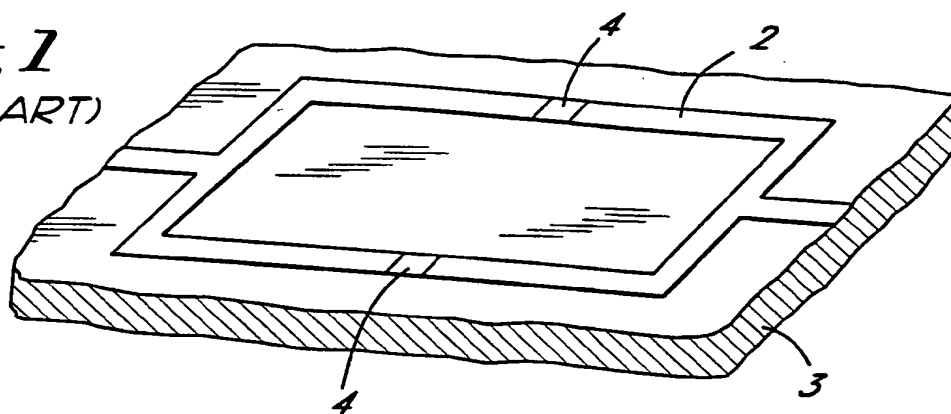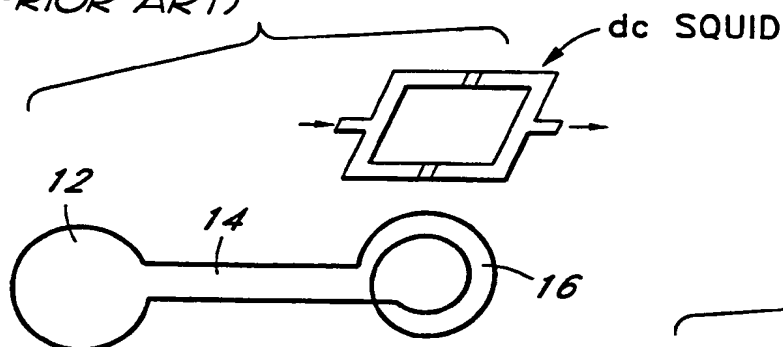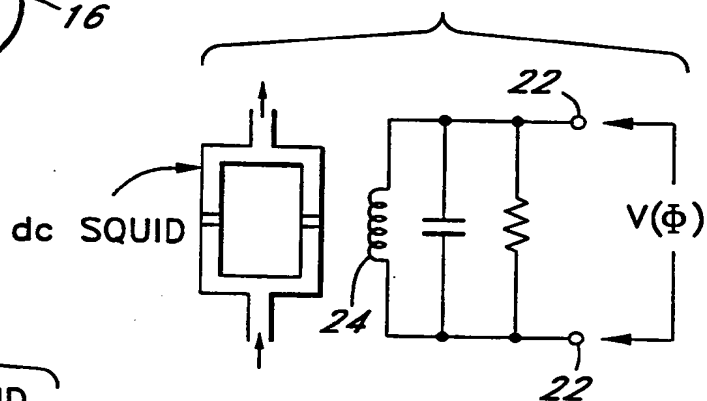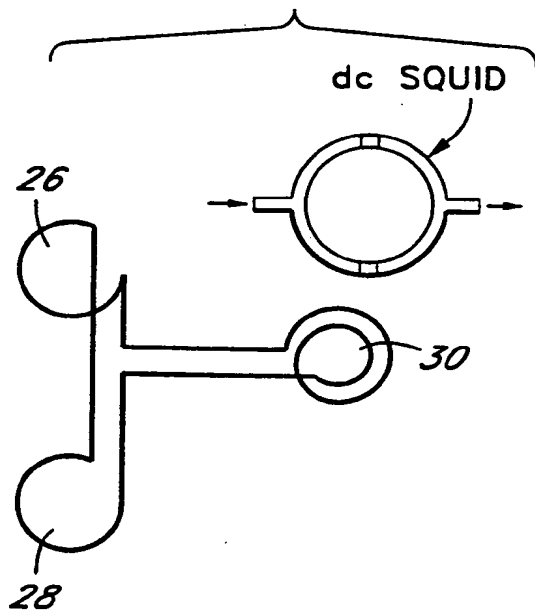
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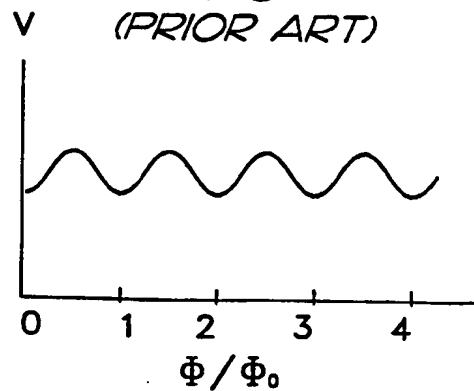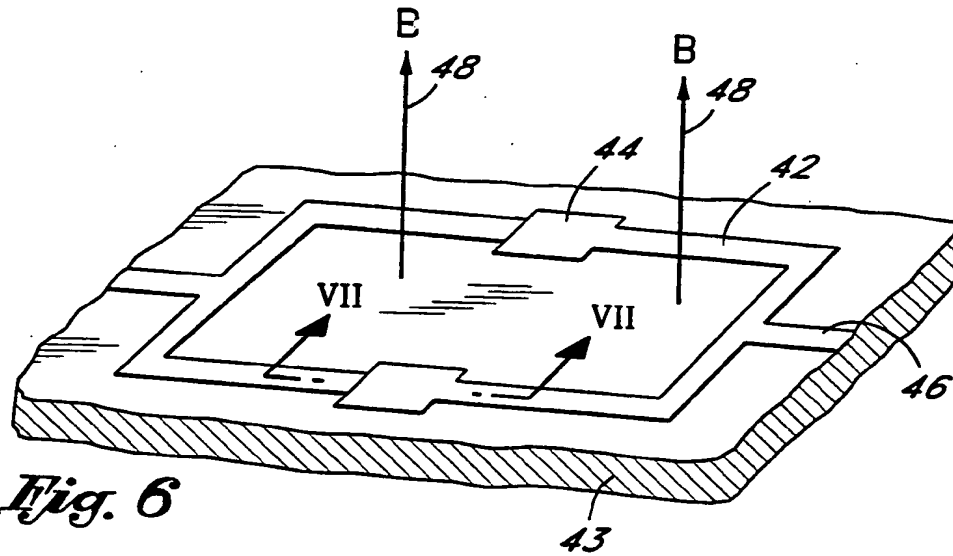
Fig. 6

Fig. 7

Fig. 8

Fig. 9

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Fig. 10

Fig. 11

Fig. 12

Fig. 13
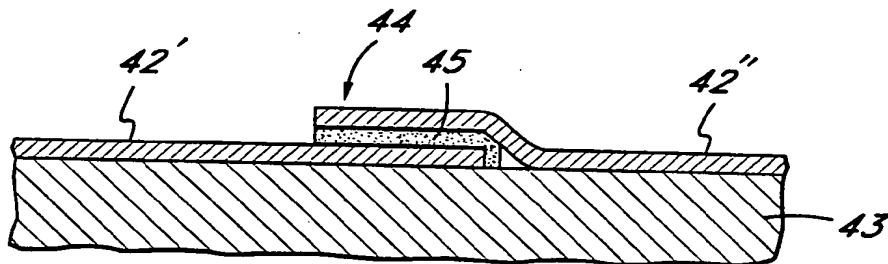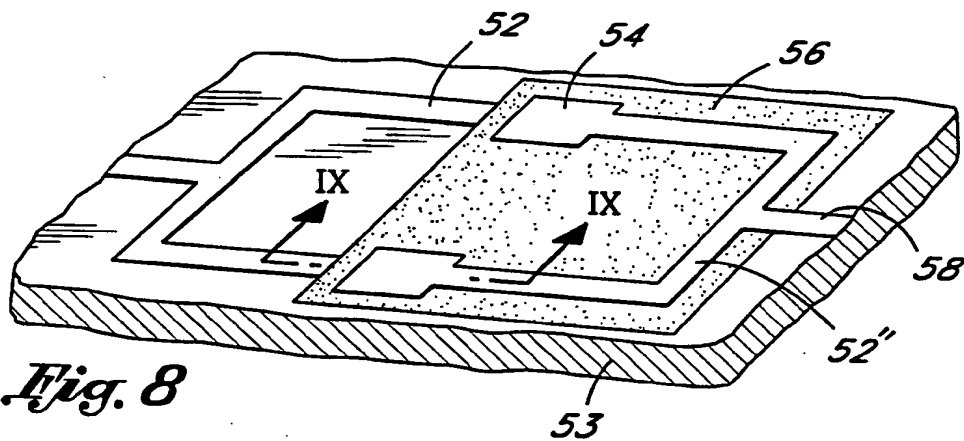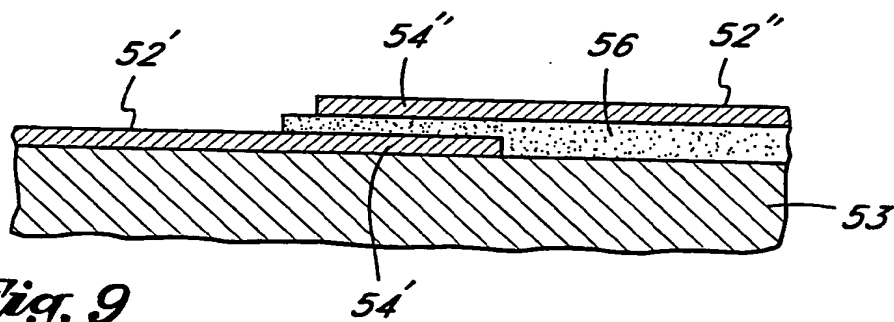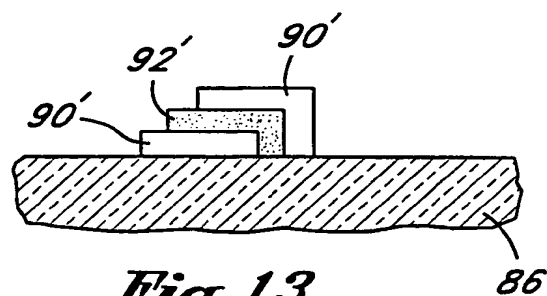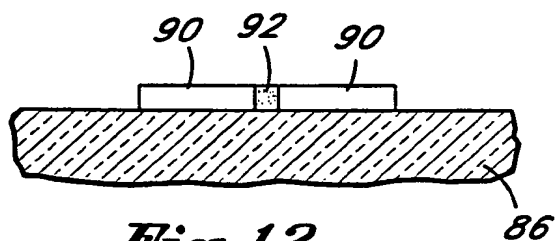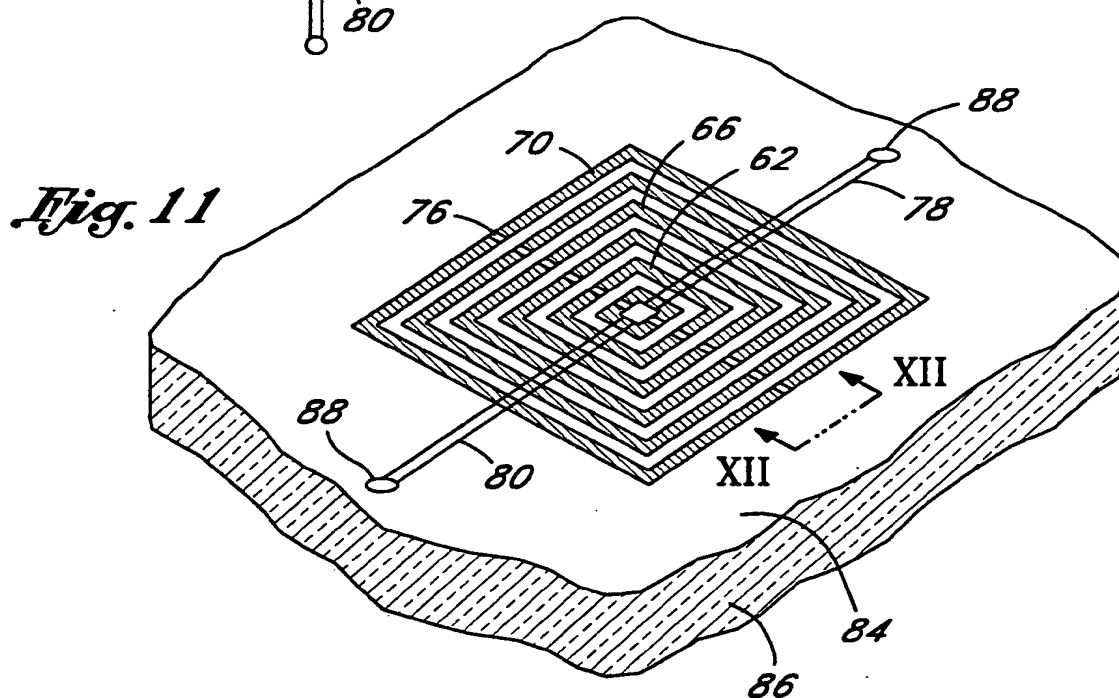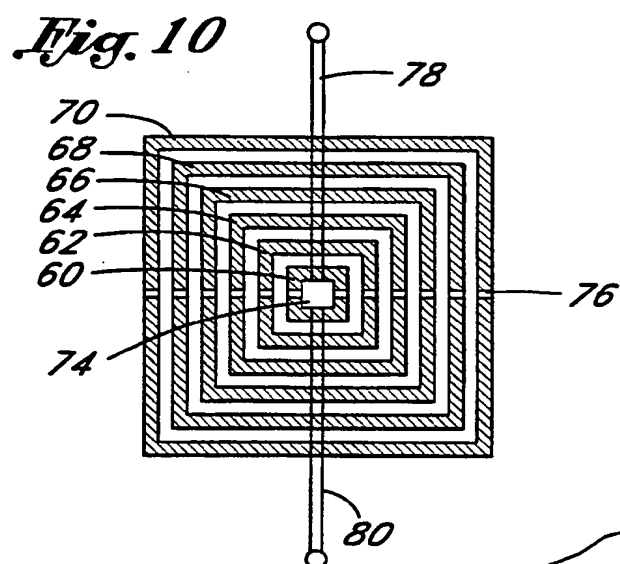
INTERNATIONAL SEARCH REPORT

International application No.

PCT/US96/09261

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :G01R 33/035
US CL   :324/248

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. :   324/248; 257/31,32,33,34,35,36; 505/845,846

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US,A, 4,982,157 (SEIFERT) 01 JANUARY 1991, see abstract	

☐ Further documents are listed in the continuation of Box C.   ☐ See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
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Date of the actual completion of the international search	Date of mailing of the international search report
18 SEPTEMBER 1996	2 9 OCT 1996

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